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Introduction

Work on the development of an interferometric system for the purpose of absolute length determination commenced in January of this year. Our goal is to develop a system capable of measurements on the order of one meter with an accuracy of 1 part in 10^9 or greater. A modified Michelson bread board with stabilized laser diode source has been assembled. Some preliminary measurements have begun using the tunable Santek laser in an FM modulation scheme[1,2]. During this same period a literature search yielded a paper by Suematsu and Takeda which discusses a promising fourier transform technique for real time data analysis[3]. We are in the process of evaluating this technique while we continue to change and up grade the system configuration.

Research

First we decided on a schematic for the Michelson breadboard, which is shown in Fig. 1. Next a list of required components was drawn up and those not available in the Photonics Branch were ordered. The Santek stabilized laser had been previously procured by NASA for interferometric experiments. Basic specifications for this laser are:

Tunable wavelength: 1.28-1.36μm,
linewidth ≤ 200kHz,
frequency fluctuation ≤ ± 5MHz
frequency stability ≤ ±100kHz over a 10 sec time period

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The configuration shown in Fig. 1 comprises three Michelson interferometers in one, using one source and one detector. The Santek diode source is optically coupled from its fiber optic output to the interferometer by a conventional lens. Light from the three legs that reflect from corner cubes 1, 2 and 3 is brought to interfere at the single photodiode detector. Signals from this detector can be recorded on disc in the computer which is additionally used for data analysis. The signals can also be displayed on a digital oscilloscope.

As has been explained by Kikuta et al.[1], and Seta and Ward[2], and others, if one modulates the laser diode output frequency by changing the drive current in a linear ramp, a beat frequency f_b will be created between a reference beam and any beam that has traveled a distance L greater than the length of the reference arm:

$$f_b = L/c\cdot[\Delta f/\Delta t] = L\cdot\Delta\lambda/(\lambda^2\cdot\Delta t) \qquad 1]$$

where $\Delta f/\Delta t$ is the change in the diode output frequency with time and c the speed of light. In Fig.1 and ignoring corner cube 3, L could be $2[d_1-d_2]$ for example. With the addition of corner cube 3, two additional interference patterns are obtained. The most important of these is that due to the path between d_1 and d_3, which can be used as a reference path difference.

Multi-beam Interferometry

In the work of Suematsu and Takeda, it is explained how non linearities in the frequency scan can be removed by using two or more frequencies and/or two or more reference interferometers, one of which provides a very precisely known optical path, L_R (reference length).[3] If the non linear behavior of the wavelength change with time is expressed as $\Delta\lambda = [\alpha_o + \Delta\alpha(t)]\cdot\Delta t$, where α_o gives the linear portion and $\Delta\alpha(t)$ the non-linear portion, then Eq.1 becomes:

$$f_b = L/\lambda^2\cdot[\alpha_o + \Delta\alpha(t)]. \qquad 2]$$

In the work of Suematsu and Takeda,

$$\alpha_o L/\lambda^2 \equiv f_s, \tag{3}$$

a constant carrier frequency produced by a perfectly linear wavelength scan.

If for a moment we assume no nonlinearities, then the second term of Eq. 2 would be zero. If there were two interferometers observing the same diode scanned radiation, then there would be two frequencies of the type in Eq. 3 present at the detector, one for each path difference. The frequency associated with the interferometer with a know path difference L_R would be $f_R = \alpha_o L_R/\lambda^2$. Taking the ratio of the frequencies for the two interferometers yields:

$$L = [f_s/f_R]\cdot L_R. \tag{4}$$

Ideally, one can determine the length of an unknown optical path difference from a known or reference path using this technique. The additional interferometric paths shown in Fig. 1 are there by explained where twice the path difference between legs d_2 and d_3 for example could be the reference length.

Fourier Transform Technique

In any real system, the wavelength change with time will not be purely linear, and the second term in Eq.2 will be important. The same information in the beat frequency is carried in the phase difference at the detector and it can be readily shown that $\Delta\phi/\Delta t = 2\pi f_b$ or $\phi(t) - \phi_o = 2\pi f_b\cdot(t - 0) = 2\pi\cdot L/\lambda^2\cdot[\alpha_o + \Delta\alpha(t)]\cdot t$. Then

$$\phi(t) = \phi_o + 2\pi f_s t + \theta(t), \tag{5}$$

$$\text{where } \theta(t) = 2\pi L\Delta\alpha(t)t/\lambda^2 \tag{6}$$

and carries the nonlinear information. These equations are Eq. 7 and 8 in the work of Suematsu and Takeda[3]. The remaining development follows directly from their work.

If the waveform in each leg of a Michelson interferometer is of the form $E = E_1 e^{i(2\pi f t+\phi_1)}$, then the interference fringe pattern will have the form $E^2 = E_1^2 + E_2^2 + 2E_1E_2\cos(\phi_2 - \phi_1)$. Masakazu and Takeda there for write the interference signal g(t) at the interferometer as

$$g(t) = a(t) + c(t)e^{2\pi i f_s t} + c^*(t)e^{-2\pi i f_s t} \qquad 7]$$

where a(t) is the intensity sum for the two beams and the additional and non-linear information is carried in c(t):

$$c(t) = E_1E_2e^{i[\theta(t) + \phi_o]}. \qquad 8]$$

If the nonlinearities in the wavelength sweep are relatively small so that $\alpha_o \gg \alpha(t)$ and if $L \gg \lambda^2/\Delta\lambda \equiv \Lambda$ the so called "synthetic wavelength", the fourier transform of g(t) separates into three regions. The region centered around f=0 contains the amplitude information which is of no importance. Two other spectra on either side centered around $\pm f_s$ contain the nonlinear phase information. Filtering out one of these regions and re- transforming retrieves c(t), [Eq. 8] from the frequency spectra. The phase information is separated from the amplitude information in Eq. 8 by taking the natural logarithm and pulling out the imaginary part.

This technique has thereby isolated the phase $\phi(t)$ given in Eq.5 above. If there is a second leg in the interferometer to provide a reference phase:

$$\phi_R = \phi_{RO} + 2\pi f_R t + \theta_R(t) \qquad 9]$$

where $f_R = \alpha_o L_R/\lambda^2$ and $\theta_R(t) = 2\pi L_R\Delta\alpha(t)t/\lambda^2$. [9a,9b]

To get rid of the constant phases in Eqs. 5 and 9, time derivatives of the phases are taken and defined as angular frequencies:

$$\omega_s(t) = d\phi_s/dt = 2\pi f_s + \dot{\theta}_s(t) = 2\pi L/\lambda\cdot\left[\alpha_o + d\{\Delta\alpha(t)t\}/dt\right], \qquad 10]$$

$$\omega_R(t) = d\phi_R/dt = 2\pi f_R + \dot{\theta}_R(t) = 2\pi L_R/\lambda \cdot \left[\alpha_o + d\{\Delta\alpha(t)t\}/dt\right]. \quad 11]$$

Taking the ratio of Eq 10 to Eq 11 and solving for L yields:

$$L = [\omega_S(t)/\omega_R(t)] \cdot L_R. \quad 12]$$

Thus the optical path difference can be computed once the angular frequencies have been obtained. Note that the nonlinearities in $\Delta\alpha(t)$ cancel out in this technique.

Discussion

Suematsu and Takeda have made measurements using two and three beam interference patterns. They find laser noise, noise in the different arms and mechanical vibrations to be limiting in their measurements. They also show that the nonlinearities in ω_i increase with increased ramp drive frequency. However they gave no numerical limits to the accuracy of which the unknown length L could be determined relative to a reference length.

Currently we are configuring our optical breadboard to reproduce their results while looking into ways to improve the concept. We plan to add a high finesse (≅ 10,000) Fabry-Perot interferometer to monitor the primary radiation from the Santek laser while at the same time maintaining three Michelson path differences. The Fabry-Perot will also give us an additional point of reference.

The method by which the angular frequencies are retrieved from the phases using computer analysis is of present concern. We must un wrap the phase information which is currently being presented as a periodic output at the frequencies f_S and f_B.

The results of Suematsu and Takeda are for modulation of the laser diode between mode-hop regions. We plan to reproduce these results and then push the technique to include mode-hops. In this case the assumptions on the small deviation in $\Delta\alpha(t)$ from α_o may no longer be quite true. This may or may not limit the fourier transform scheme of retrieving the phase information and we can learn this only by experimental investigation.

As the nonlinear portions in the derivatives of the phases cancel out of the ratio used in length determination [Eq. 12], the technique may still work across mode hop regions. This would allow length ratio determinations to be limited primarily by the fundamental stability of the source laser diode.

During the coming months we will be investigating the above concepts, looking into different methods to analyze and process our signals, improving on the experimental setup and determining the limitations of the system.

References

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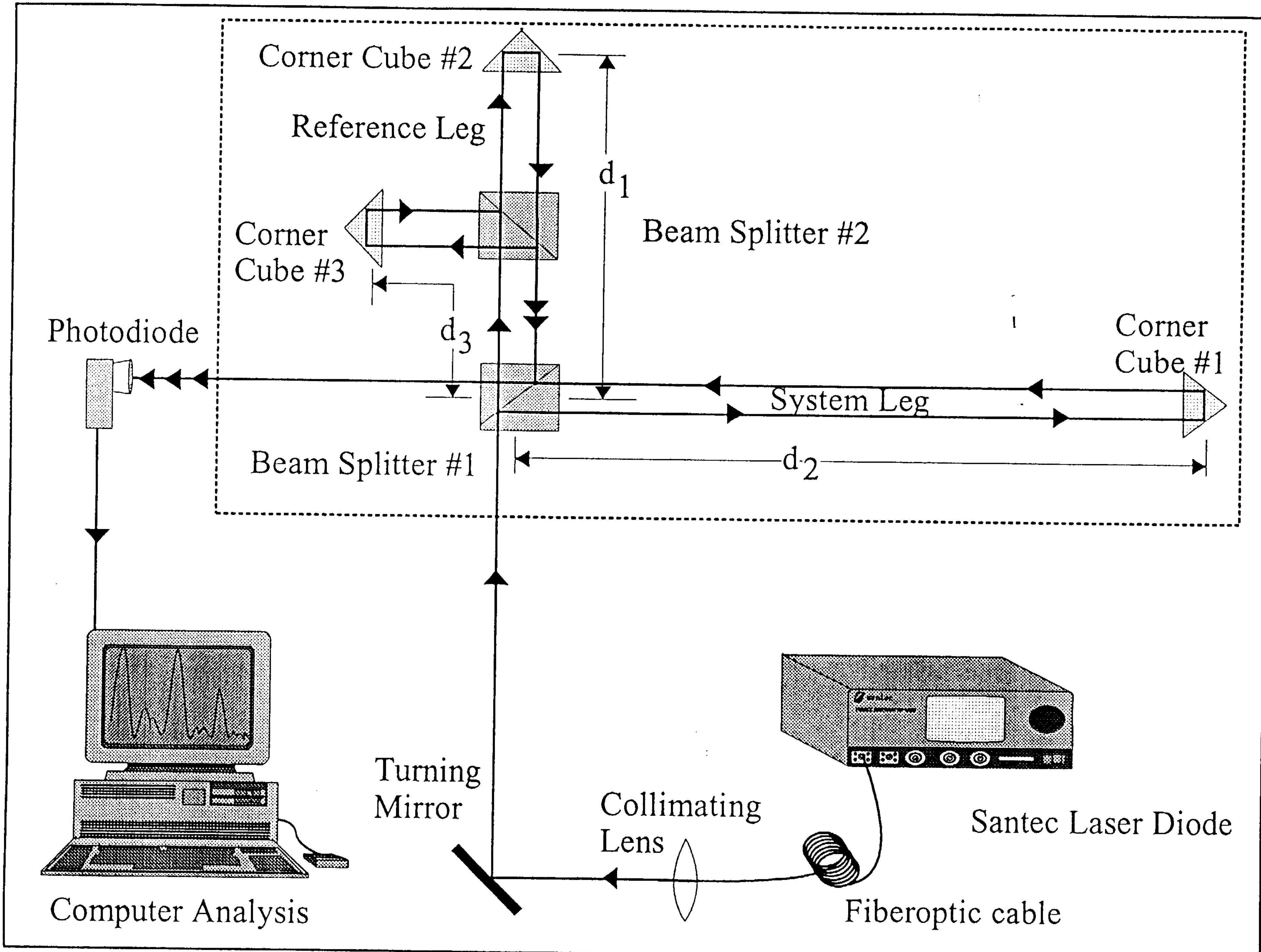
Corner Cube #2
Reference Leg
d_1
Corner
Cube #3
Beam Splitter #2
Photodiode
d_3
Corner
Cube #1
System Leg
Beam Splitter #1
d_2
Turning
Mirror
Collimating
Lens
Santec Laser Diode
Computer Analysis
Fiberoptic cable

Fig 1